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**NONLINEAR ROTORCRAFT ANALYSIS -
EXPERIMENTAL AND ANALYTICAL**

FINAL REPORT

AUTHOR
B. H. Tongue

6 November 1988

U.S. ARMY RESEARCH OFFICE
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GEORGIA INSTITUTE OF TECHNOLOGY
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1. PROBLEM STUDIED

A parallel effort involving both analytical and experimental work was performed to allow a deeper understanding of the limit cycle behavior of rotorcraft and of the implication of this behavior for the safe operation of such rotorcraft. The theoretical development encompassed articulated and hingeless rotors with a great enough number of included degrees of freedom to allow accurate predictions of a simplified rotorcraft's responses. The experimental model allowed the simulation of both hingeless and articulated rotors in ground resonance. The purpose of the above work was to identify the regimes of helicopter operation that can support limit cycling and the range of excitations the system can withstand before entering a limit cycle. Both ground and air resonance behaviors were analytically investigated.

2. MAIN RESULTS

The research program proved to be extremely successful. A sophisticated harmonic balance procedure was applied to the fully nonlinear ground resonance model and was shown to capture all of the essential dynamical behavior of the system. This modeling went substantially beyond any of the nonlinear ground resonance analyses that preceded it. Construction of the equations of motion and the subsequent solution of these equations was greatly aided by an extensive use of symbolic manipulation. The results showed that destructive, high amplitude limit cycles could exist, not only in the linearly unstable regime, but also at rotor speeds for which linear analyses would predict purely stable behavior. Thus one would expect that a strong perturbation to the craft, such as a hard landing, could push the system into a high amplitude limit cycle that would lead to the destruction of the aircraft. These predictions were fully verified by the experimental ground resonance rig. The experimental parameters were entered into the generic analytical model and led to responses that were very closely matched by the behavior of the actual model. Thus the findings were shown not to be simply academic exercises, but responses that were physically realizable. Parametric studies were completed to indicate the response of the system under a widely varying set of physical conditions. The generic methodology of the analyses can easily be applied to a variety of rotor problems.

The air resonance study led to a moderately complicated structural model having aerodynamic interactions. The complexity of the nonlinear response made a limit cycle analysis computationally infeasible, thus leading to a use of more traditional numerical integration. The same sorts of behavior that were predicted for the ground resonance model were shown to be possible in the air resonance model, i.e. limit cycling in a linearly stable region of rotor speeds. The effect of various nonlinearities on the response was assessed, with the conclusion that the most significant nonlinear effects were engendered from discrete nonlinear structural elements. This model was also examined for more complicated nonlinear effects than simple harmonic limit cycles. The most notable outcome of this work was the demonstration that under a harmonic excitation (such as occurs with Higher Harmonic Control) the rotor response can become chaotic. It is believed that this is the first time that the existence of chaos has been indicated in a rotorcraft.

3. PUBLICATIONS AND PRESENTATIONS

1. "Construction and Analysis of a Simplified Nonlinear Ground Resonance Model," M.D. Janowski and B.H. Tongue, *Journal of Sound and Vibration*, **122**, No. 2, 22 April 1988, pp. 233-242.
2. "Nonlinear Rotorcraft Analysis," B.H. Tongue and G.T. Flowers, *International Journal of Nonlinear Mechanics*, **23**, No. 3, 1988 pp. 189-204.
3. "Nonlinear Rotorcraft Analysis using Symbolic Manipulation," G. T. Flowers and B. H. Tongue, *Applied Mathematical Modelling*, **12**, April 1988, pp. 154-160.
4. "Interpolated Cell Mapping of Dynamical Systems," B.H. Tongue and K. Gu, *ASME Journal of Applied Mechanics*, **55**, No 2, June 1988, pp. 461-467.
5. "On Obtaining Global Nonlinear System Characteristics Through Interpolated Cell Mapping," *Physica* **28D**, 1987, pp. 401-408.
6. "An Experimental Study of the Effects of Nonlinearities on Ground Resonance," G.T. Flowers and B.H. Tongue, submitted to the *Journal of Guidance, Control and Dynamics*, 1988.
7. "Nonlinear Air Resonance," G.T. Flowers and B.H. Tongue, in preparation.
8. "On the Existence of Chaotic Responses in a Rotating Blade," B.H. Tongue and G.T. Flowers, in preparation.
9. "Nonlinear Rotorcraft Analysis," presented at the AFOSR/ARO Conference on Nonlinear Vibrations, Stability, and Dynamics of Structures and Mechanisms, VPI&SU, Blacksburg, VA, March 23-25, 1987.
10. "Ground Resonance - A Nonlinear Analysis," presented at the Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Boca Raton, November 18-20, 1987.
11. "Linearization Considerations for a Simple Air Resonance Model," presented at the Second Technical Workshop on Dynamics and Aeroelastic Stability Modeling of Rotorcraft Systems, Boca Raton, November 18-20, 1987.
12. "Dynamical Behavior of a Nonlinear Air Resonance Model," to appear in the proceedings of the AIAA/ASME/ASCE/AHS/ASC 30th Structures, Structural Dynamics, and Materials Conference, 1989.

4. PERSONNEL

Principal Investigator: Benson H. Tongue

Graduate Student: Michael Janowski, "Analysis of a Simplified Nonlinear Ground Resonance Model"
M.S. Thesis, 1986.

Graduate Student: George T. Flowers, "A Study of the Effects of Nonlinearities on the Behavior of Rotorcraft in Ground and Air Resonance"
Ph.D. Thesis, 1988.

Graduate Student: Keqin Gu, "Determining Attractors, Basins of Attraction and Trajectory Control of Nonlinear Dynamical Systems"
Ph.D. Thesis, 1988.

Graduate Student: Philip FitzSimons, Ph.D. expected 1989.